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RESEARCH MEMORANDUM

EFFECT OF INLET-DUCT LENGTH IN UNIFORM-FLOW

FIELD ON TURBOJET-ENGINE OPERATION

By Robert J. Lubick, Louis J. Chelko, and Lewis E. Wallner

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EFFECT OF INLET-DUCT LENGTH IN UNIFORM-FLOW FIELD ON TURBOJET-ENGINE OPERATION

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SUMMARY

A high-pressure-ratio axial-flow turbojet engine was operated in the Lewis altitude wind tunnel to determine the effect of inlet-duct length on engine operation. Data were obtained with a short bellmouth inlet and with a 20-foot duct section of uniform diameter between the inlet and the compressor. Both steady-state and transient data were obtained in an effort to determine any differences in engine characteristics attributable to inlet-duct length.

Although the additional duct length increased the inlet velocity gradient somewhat, there was no noticeable effect on steady-state compressor pressure ratio or exhaust-gas temperature. The engine time constants and stall limits in terms of both compressor pressure ratio and engine fuel flow were unaffected by inlet-duct length. Increased duct length increased the time required for surge recovery and sometimes resulted in combustion blow-out. Over at least part of the speed range, lower-amplitude pressure oscillations and higher frequencies were obtained during surge with the long-duct inlet compared with the bellmouth inlet.

INTRODUCTION

To measure adequately the performance of a turbojet engine during fuel transients requires complex instrumentation. Therefore, the practical way to collect experimental data of this type has been in altitude test facilities where space, weight, and time considerations are not the critical factors they are in flight testing. Before altitude-facility data can be assumed representative of actual flight results, however, several factors must be considered, among which are velocity profiles entering the engine, variations in inlet total pressure during changing engine air requirements, and differences in inlet-duct volume between flight and altitude-facility engine installations. This paper is particularly concerned with the last problem.

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Duct volume at the compressor exit has been known to have a strong influence on engine performance or surge characteristics (see ref. 1). In addition, certain inlet-ducting arrangements have been reported to produce "organ-piping" effects at the compressor entrance. When an inlet duct is operating in a nonuniform-flow field, increasing the duct length has been reported to improve the pressure profiles at the duct exit (ref. 2). This report is an effort to determine whether a simple extension of the inlet ducting (increasing duct volume) with no change in diameter or flow direction has any effect on either the steady-state or transient performance of the engine. In altitude test facilities the inlet-duct length may vary from a bellmouth attached directly to the compressor to a 20-foot or longer inlet duct necessitated by the arrangement of the engine within the test chamber. However, the question of inlet-duct volume is not confined to altitude test facilities; it also arises for engines mounted in various aircraft configurations, such as a pod-type compared with fuselage installations.

In order to determine the effects of inlet-duct length in a uniform-flow field on engine performance, a turbojet engine was operated in the NACA Lewis altitude wind tunnel with a short bellmouth inlet and with a 20-foot duct section of uniform diameter placed between the inlet and the compressor. Steady-state and transient engine data were obtained for a range of engine speeds at altitudes between 15,000 and 50,000 feet at a flight Mach number of 0.2. The effects of inlet-duct length on steady-state performance, engine acceleration, fuel-flow and pressure-ratio stall limits, and surge characteristics of the engine-duct combination were investigated.

SYMBOLS

f	surge frequency, cps
N	engine speed, rpm
P	total pressure, lb/sq ft abs
$P_{2,max}$	compressor-discharge total pressure at stall point, lb/sq ft abs
ΔP_2	compressor-discharge total-pressure fluctuation during surge, lb/sq ft abs
T	total temperature, $^{\circ}R$ ($^{\circ}F$ abs)
t	time in surge, sec
V	velocity, ft/sec
w_f	fuel flow, lb/hr

θ temperature-correction factor, ratio of total temperature to NACA standard sea-level temperature of 518.7° R

τ time constant, sec

Subscripts:

av average

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d distorted

l local

u undistorted

1 engine inlet

2 compressor outlet

3 exhaust-nozzle inlet

APPARATUS

Engine

An axial-flow turbojet engine, which was in the 10,000-pound-thrust class with an air flow of about 160 pounds per second, was used in this study. The engine was equipped with compressor bleed valves to afford improved stall margin during acceleration. The standard engine fuel control was replaced by a constant-pressure-drop control, which permitted rapid changes in fuel flow.

Instrumentation

Instrumentation installed at each of the measuring stations is indicated in figure 1. The transient data were recorded on multiple-channel oscillographs. Pressure variations were measured by means of pressure transducers, which converted pressure changes into electrical signals for input into the oscillograph after appropriate amplification. Engine speed was measured with a high-speed electronic counter. Throttle-valve position was used as a measure of engine fuel flow, because a constant pressure drop was maintained across the throttle.

Inlet Configuration

A diagram showing the two engine-inlet-duct combinations is shown in figure 2. For the configuration hereinafter referred to as the "bellmouth inlet," a bellmouth was directly connected to a 24-inch instrumentation section, which was in turn connected to the engine-inlet flange. For the "long-duct inlet," the bellmouth was separated from the instrumentation section by a 20-foot cylindrical section.

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PROCEDURE

Steady-state data were obtained with the two engine-inlet configurations at simulated altitudes of 15,000, 35,000, and 50,000 feet at a nominal flight Mach number of 0.2. At each flight condition the engine was operated over the full speed range with the compressor bleeds in both the open and closed positions. For each steady-state condition, comprehensive pressure and temperature measurements were made at all the instrumentation stations indicated in figure 1. In addition to the runs made to determine differences in the steady-state operation, step increases in fuel flow were introduced into the engine to study any possible effects of duct length on acceleration characteristics. Various-sized fuel-flow steps were made to determine possible effects of inlet-duct length on acceleration rates without surge, fuel-flow stall limits, compressor-pressure-ratio stall limits, engine time constants, pressure oscillations during surge, and frequency. In order to determine these surge characteristics, fuel-flow rates resulting in surge were not reduced until a temperature limit, speed limit, or natural recovery was obtained.

RESULTS AND DISCUSSION

Steady-State Characteristics

Velocity profiles that occurred at the compressor inlet for the bellmouth and long-duct inlets are shown in figure 3, where relative inlet velocity is plotted as a function of passage height for altitudes of 15,000 and 50,000 feet. The resulting velocity gradient with the long duct is about 3 times that obtained with the bellmouth. Deviations in total pressure, presented in figure 4, indicate a pressure deficiency of about 2 percent at the blade tips due to the build-up of boundary layer in the long-duct inlet $\Delta P_{1,l}/P_{1,av} \approx 0.02$. This pressure deficiency is actually much smaller than that obtained in flight with many engine installations. From inlet pressure distortion tests, where interstage instrumentation was installed, a 10-percent change in ratio of distorted to undistorted total pressure at the inlet was reduced to $4\frac{1}{2}$ percent in

the first stage and practically disappeared in the succeeding stages (fig. 5). From the data in figure 4, then, it might be expected that the long-duct inlet (with an inlet total-pressure profile of less than 2 percent) would not produce sizeable effects on the steady-state performance. This is demonstrated by the plots of compressor pressure ratio, engine pressure ratio, and exhaust temperature in figures 6 to 8, which show no difference between the data for the two inlet configurations. This result is similar to that reported in reference 3 for an
3733 engine of different design. From these data it was concluded that the steady-state performance was not affected by the variation in inlet-duct length.

Acceleration Characteristics

A typical acceleration with the two inlet configurations at comparable conditions is presented in figure 9, where engine speed is shown as a function of time for a step increase in fuel flow. The two fuel bursts, which were started at about the same initial speed, have similar acceleration histories. The slight deviations in speed at the end of the transient arise from slightly different final fuel flows. A direct comparison of acceleration characteristics for a wide range of conditions is presented in figure 10, where the corrected time constant is plotted as a function of engine speed. Inlet-duct length has no effect on the time constant for various altitudes, engine speeds, and compressor bleed positions. Compressor-pressure-ratio histories for accelerations from three different initial speeds are shown in figure 11. For the two inlet-duct configurations, the transient pressure ratios are almost coincident during the entire acceleration for these equal-sized fuel steps from the same initial speeds. It can be concluded, then, that changing inlet-duct length does not affect the stall-free engine-acceleration characteristics.

Compressor Stall Limits

Fuel steps sufficiently large to cause compressor stall were introduced to the engine in order to obtain the compressor stall line for both inlet-duct configurations. Data obtained with the compressor bleeds in the closed and open positions are shown in figures 12(a) and (b), respectively. There is no consistent effect of inlet-duct length on compressor stall-limit lines. Sufficient fuel steps were made to determine the amount of fuel required to cause compressor surge over a range of speeds. In figure 13, data are shown for 50,000 feet, because at lower altitudes it was difficult to obtain accurately controlled fuel increases. Disregarding the data scatter, which is typical for high-altitude fuel-flow data, the inlet-duct configuration does not seem to affect the stall fuel-flow line.

Surge Characteristics

The effects of inlet-duct length on engine surge characteristics, including frequency, amplitude, and duration of pressure oscillation, are presented in figures 14 to 17. The time behavior of engine variables required to describe engine surge, for a typical acceleration following a step increase in fuel flow, is presented in figure 14. A step increase in fuel flow just large enough to reach the compressor stall limit and thereby cause engine surge is shown in the figure. Immediately following the increase in fuel flow, compressor-outlet pressure rises to a maximum (stall point, $P_{2,max}$), drops off suddenly, and is followed by successive surge oscillations of magnitude ΔP_2. Engine speed continues to increase during the entire transient but at a somewhat faster rate after surge recovery is reached. For this transient, the engine remained in surge for 1.9 seconds; after sufficient acceleration had taken place and fuel flow was no longer excessive, natural surge recovery was obtained.

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The time required for surge recovery is shown in figure 15 for a series of accelerations with both inlet-duct configurations. The faired curves approximate the lowest fuel-flow steps required for engine surge; larger fuel steps would lengthen the time in surge. Although there is considerable scatter to this data, surges obtained with the long-duct inlet, for a large part of the speed range shown, consistently required a longer time for natural surge recovery to occur. In addition, during surge, combustion blow-out occurred at high engine speeds for bleeds-closed operations with the long-duct inlet. No blow-out points were obtained with the bellmouth configuration at the same flight condition.

The amplitude of the compressor-discharge pressure oscillations during engine surge is shown in figure 16. The pressure oscillations are represented by the ratio of compressor-discharge pressure variation during surge divided by the discharge pressure just prior to surge ($\Delta P_2/P_{2,max}$, see fig. 14). At high speeds, the two inlet configurations have the same surge amplitude; at low speeds, however, the oscillations with the bellmouth inlet are somewhat larger than those obtained with the long duct. As would be expected, the low-amplitude points with the long duct oscillate at a relatively high frequency, as can be seen from the data in figure 17, which is a plot of frequency against engine speed. An increase in duct length, then, tends to increase the time in surge and result in smaller surge oscillations at higher frequency over at least part of the engine speed range. This frequency effect is opposite to the compressor-exit-volume effect on surge frequency stated in reference 4, where it was found that reduction in discharge volume increased the surge frequency.

SUMMARY OF RESULTS

A study of the effect of inlet-duct length in a uniform-flow field on turbojet-engine operation was conducted in the NACA Lewis altitude wind tunnel. The engine was operated with a bellmouth inlet connected to the compressor and with the bellmouth separated from the compressor by a 20-foot cylindrical duct section. The additional duct length increased the velocity gradient somewhat at the compressor inlet but had 3733 no measurable effect on the steady-state performance. The engine time constants and the compressor stall limits in terms of both compressor pressure ratio and engine fuel flow were unaffected by inlet-duct length. Increased duct length raised the time required for surge recovery and sometimes resulted in combustion blow-out. Over at least part of the speed range, lower-amplitude pressure oscillations and higher frequencies were obtained during surge with the long-duct inlet compared with the bellmouth inlet.

In conclusion, then, changes in inlet-duct length where flow distortions are not present have no appreciable effect on engine performance up to the stall limit; however, the surge characteristics are altered somewhat.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 16, 1955

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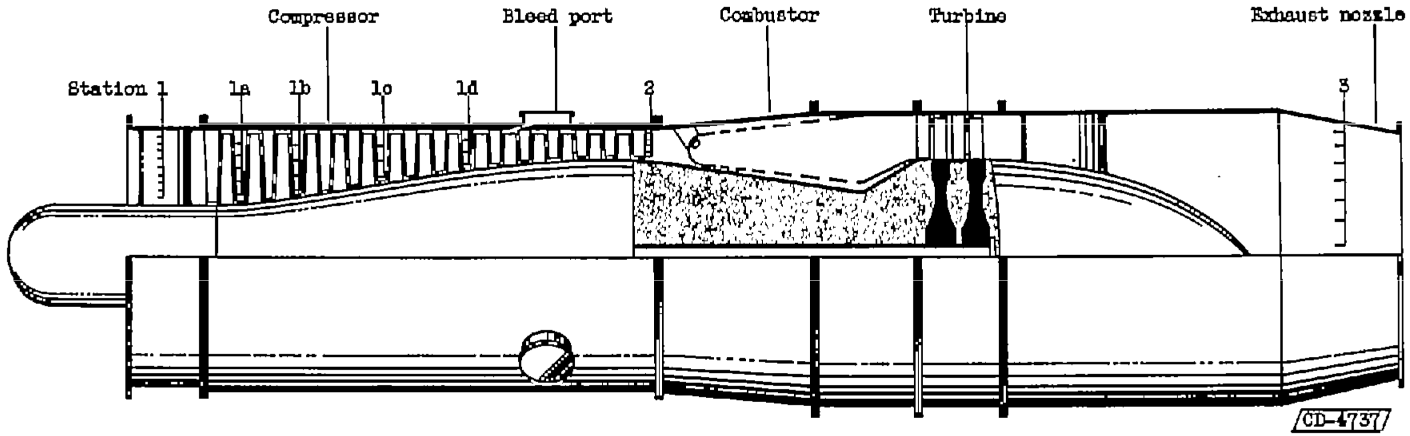
4. Emmons, H. W., Pearson, C. E., and Grant, H. P.: Compressor Surge and Stall Propagation. Trans. A.S.M.E., vol. 77, no. 4, May 1955, pp. 455-467; discussion, pp. 467-469.



Steady-State Instrumentation

Station	Total-pressure probes	Static-pressure probes	Thermocouple probes
1	42	16	16
1 a	15	2	15
1 b	12	2	12
1 c	12	2	12
1 d	18	--	9
2	20	--	12
3	24	4	24

Transient Instrumentation

Measured quantity	Station no.	Steady-state instrumentation	Transient sensor
Inlet total pressure	1	Manometer	Strain-gage pressure transducer
Compressor-outlet total pressure	3	Manometer	Strain-gage pressure transducer
Engine speed	-	Electronic counter	Electronic counter
Fuel flow	-	Rotameter	Throttle position (constant pressure drop)

Figure 1. - Schematic diagram of turbojet engine showing location and amount of instrumentation.

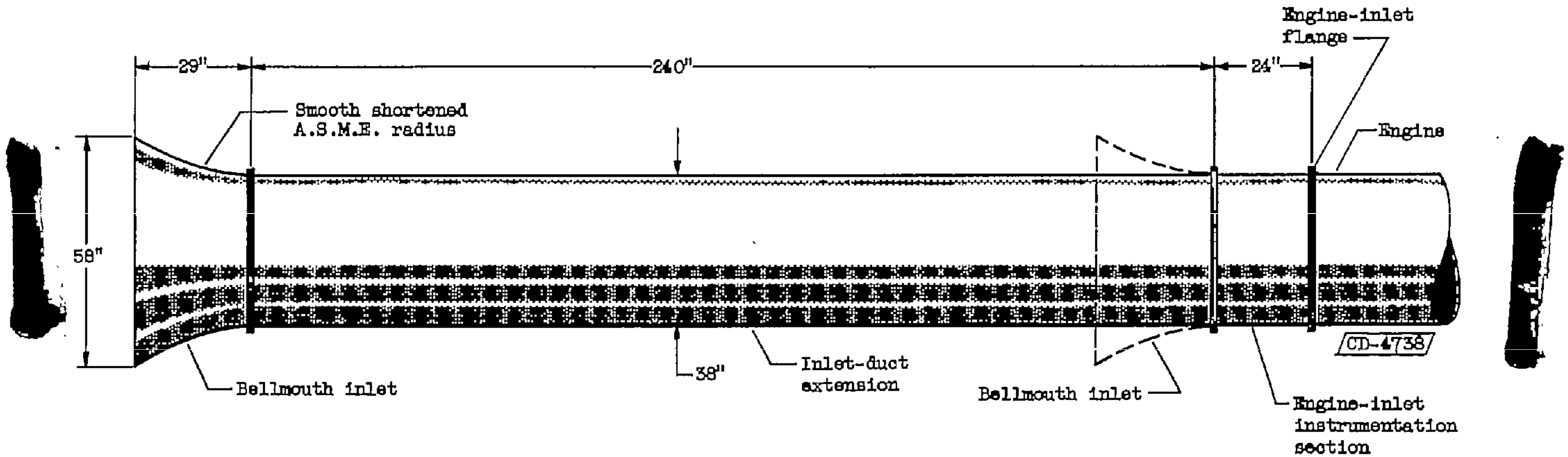
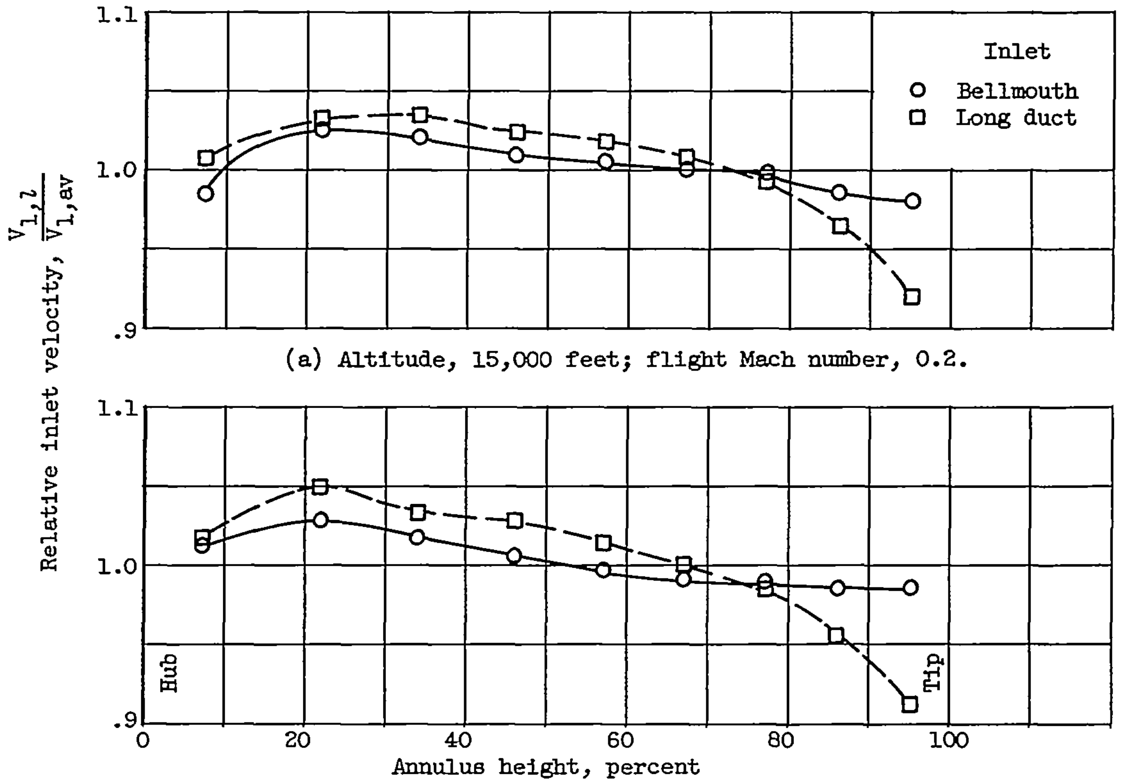


Figure 2. - Sketch of inlet ducting used in turbojet-engine installation.



(a) Altitude, 15,000 feet; flight Mach number, 0.2.

(b) Altitude, 50,000 feet; flight Mach number, 0.2.

Figure 3. - Comparison of inlet velocity profiles with bellmouth and long-duct inlets. Corrected engine speed, 103 percent rated.

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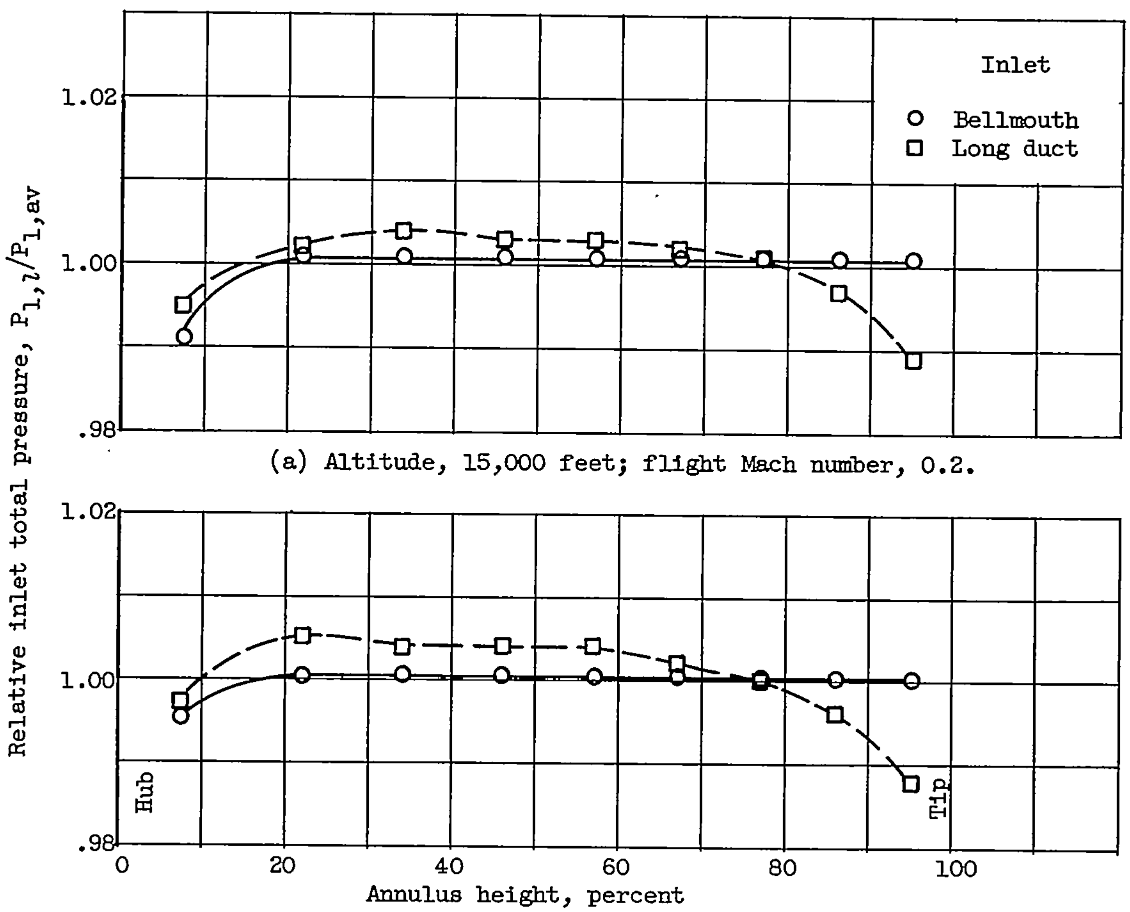

(a) Altitude, 15,000 feet; flight Mach number, 0.2.

(b) Altitude, 50,000 feet; flight Mach number, 0.2.

Figure 4. - Comparison of inlet total-pressure profiles obtained with bellmouth and long-duct inlets. Corrected engine speed, 103 percent rated.

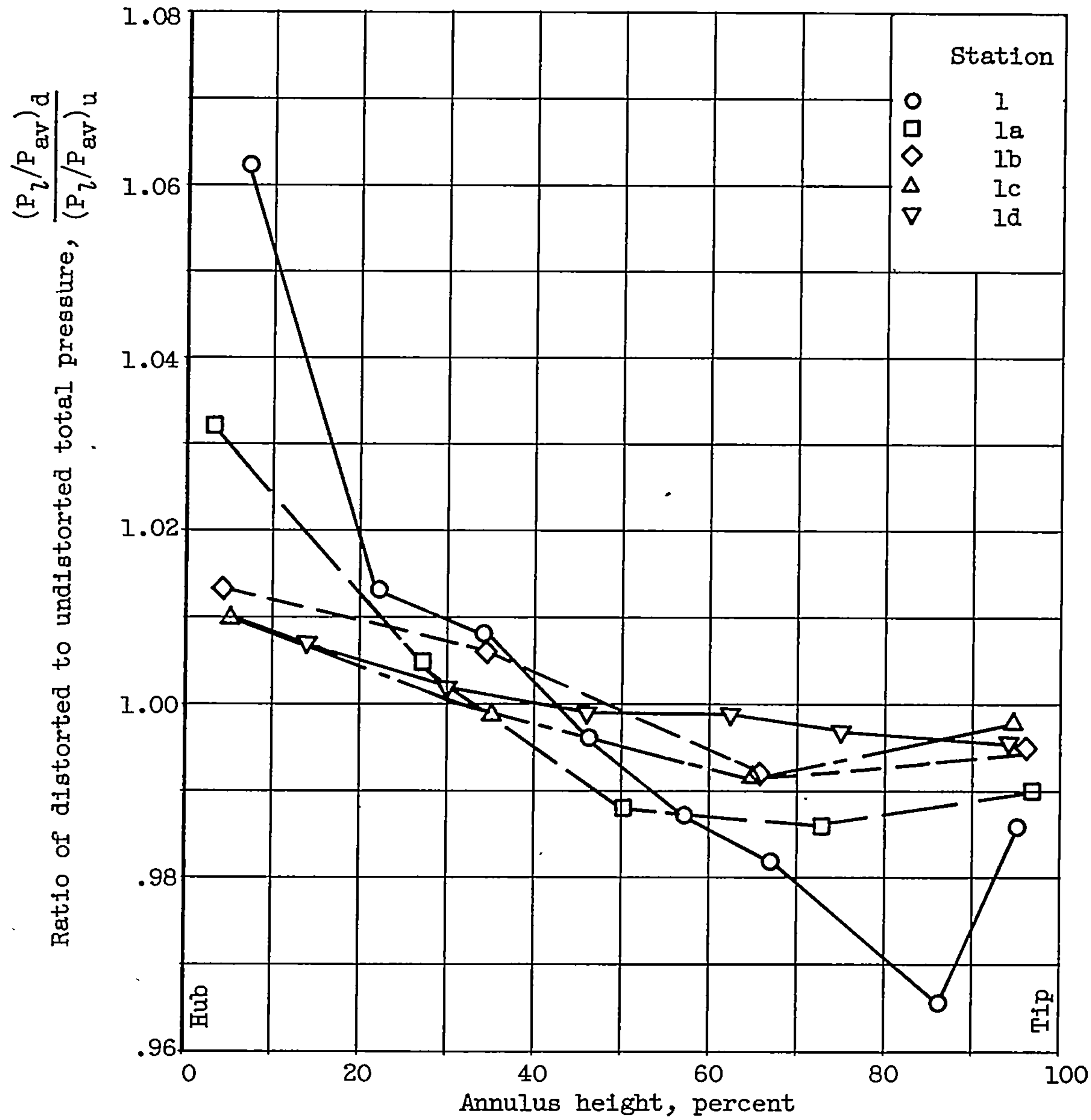

Figure 5. - Dissipation of radial inlet pressure distortion through compressor.

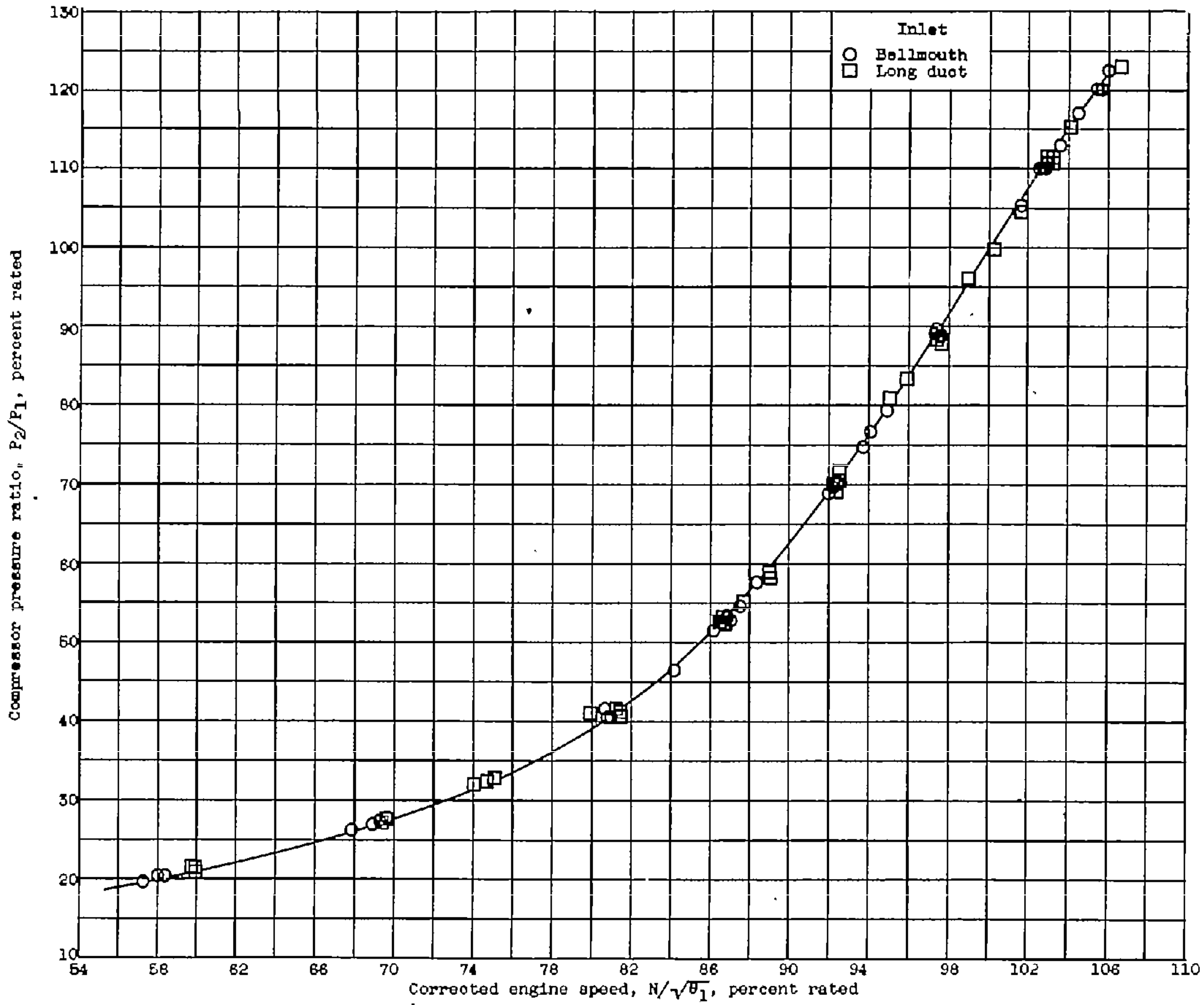

Figure 6. - Effect of inlet-duct length on steady-state compressor pressure ratio. Altitude, 35,000 feet; flight Mach number, 0.2; compressor bleeds open.

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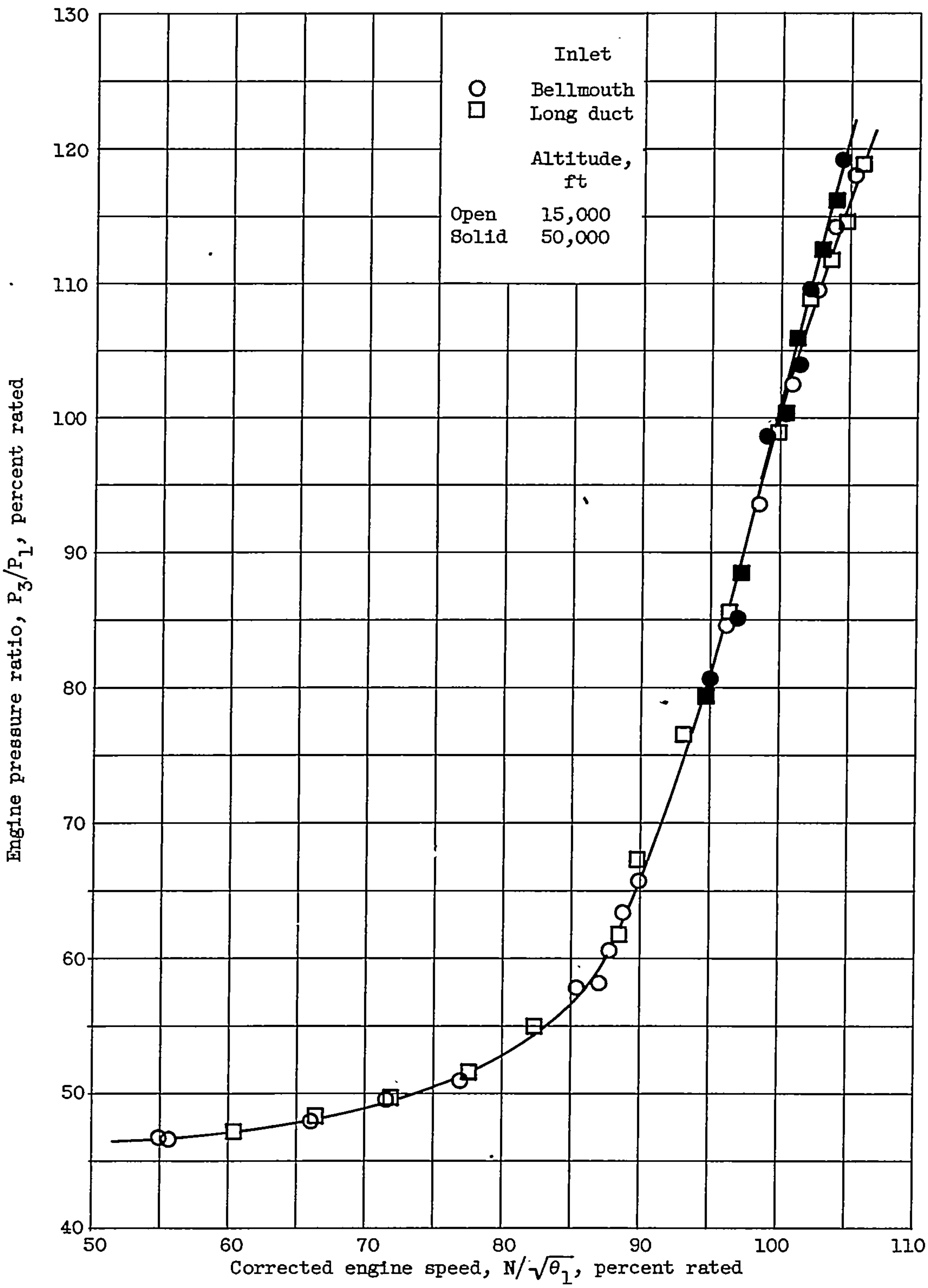

Figure 7. - Effect of inlet-duct length on engine pressure ratio. Flight Mach number, 0.2; compressor bleeds closed.

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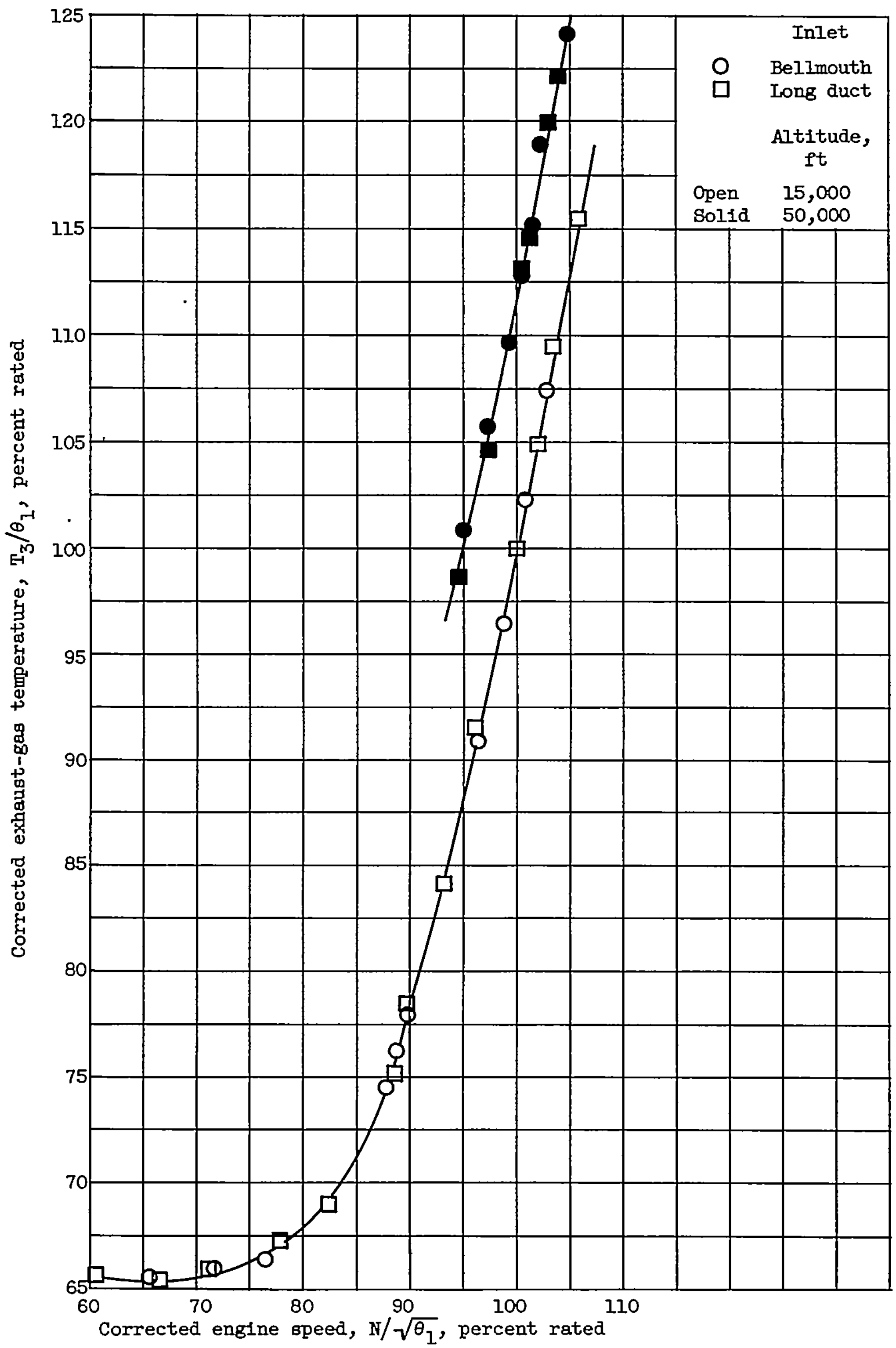

Figure 8. - Effect of inlet-duct length on exhaust-gas temperature. Flight Mach number, 0.2; compressor bleeds closed.

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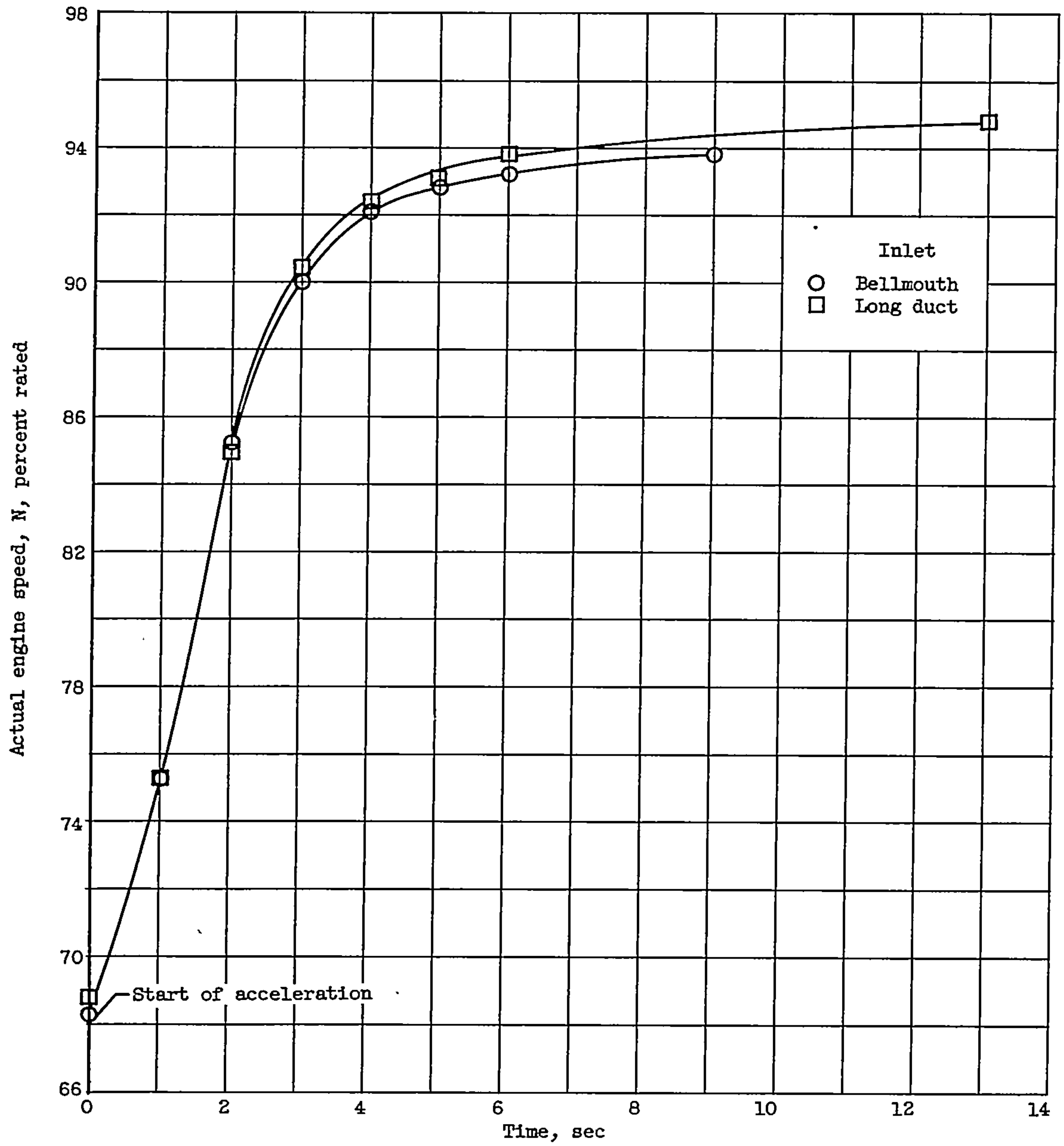
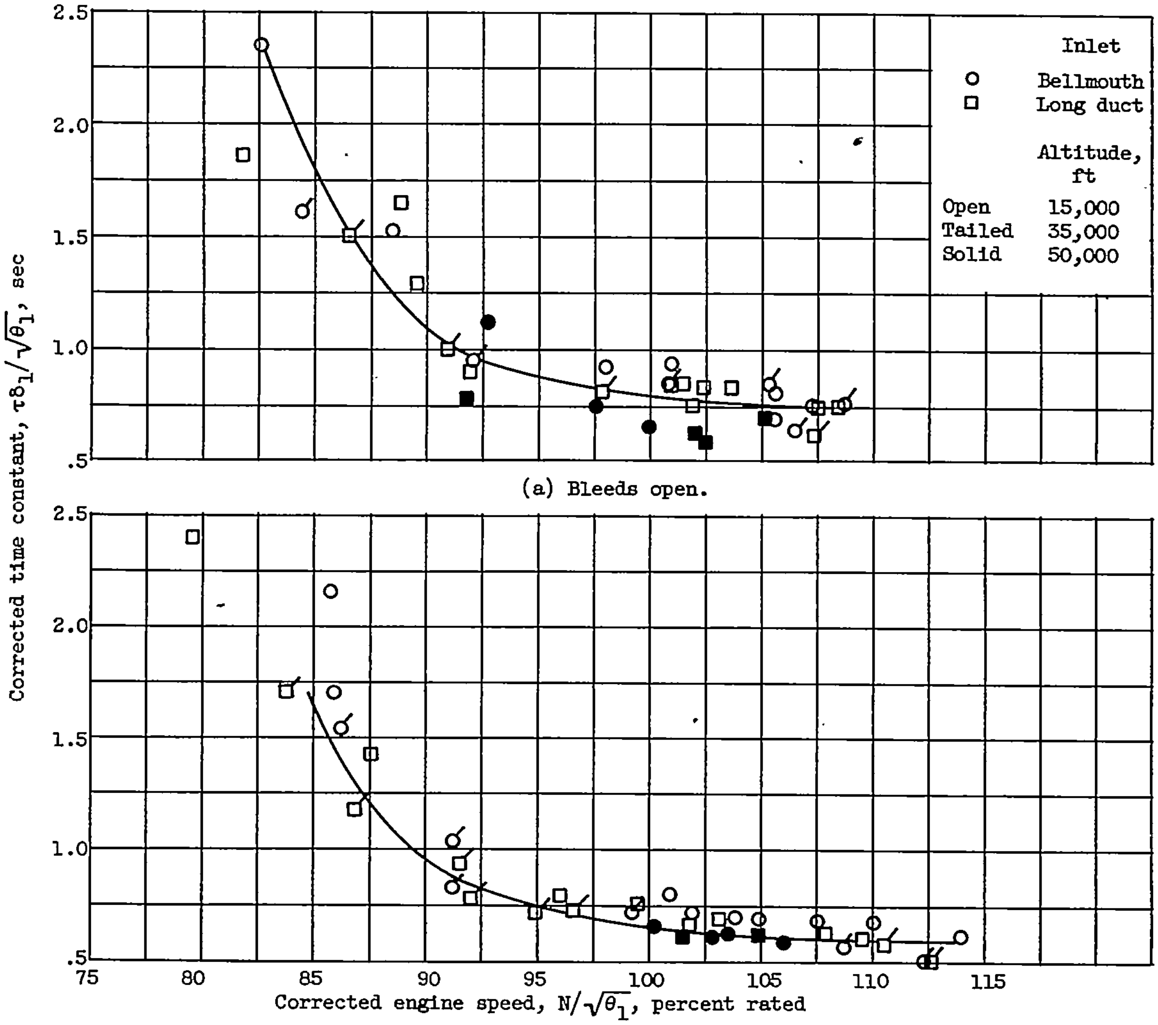


Figure 9. - Effect of inlet-duct length on engine acceleration from similar initial speeds and final fuel flows. Altitude, 15,000 feet; flight Mach number, 0.2; compressor bleeds closed. (Speed deviations toward end of accelerations arise from slightly different final fuel flows.)



(a) Bleeds open.

(b) Bleeds closed.

Figure 10. - Effect of inlet-duct length on engine time constants with compressor bleeds open and closed. Flight Mach number, 0.2.

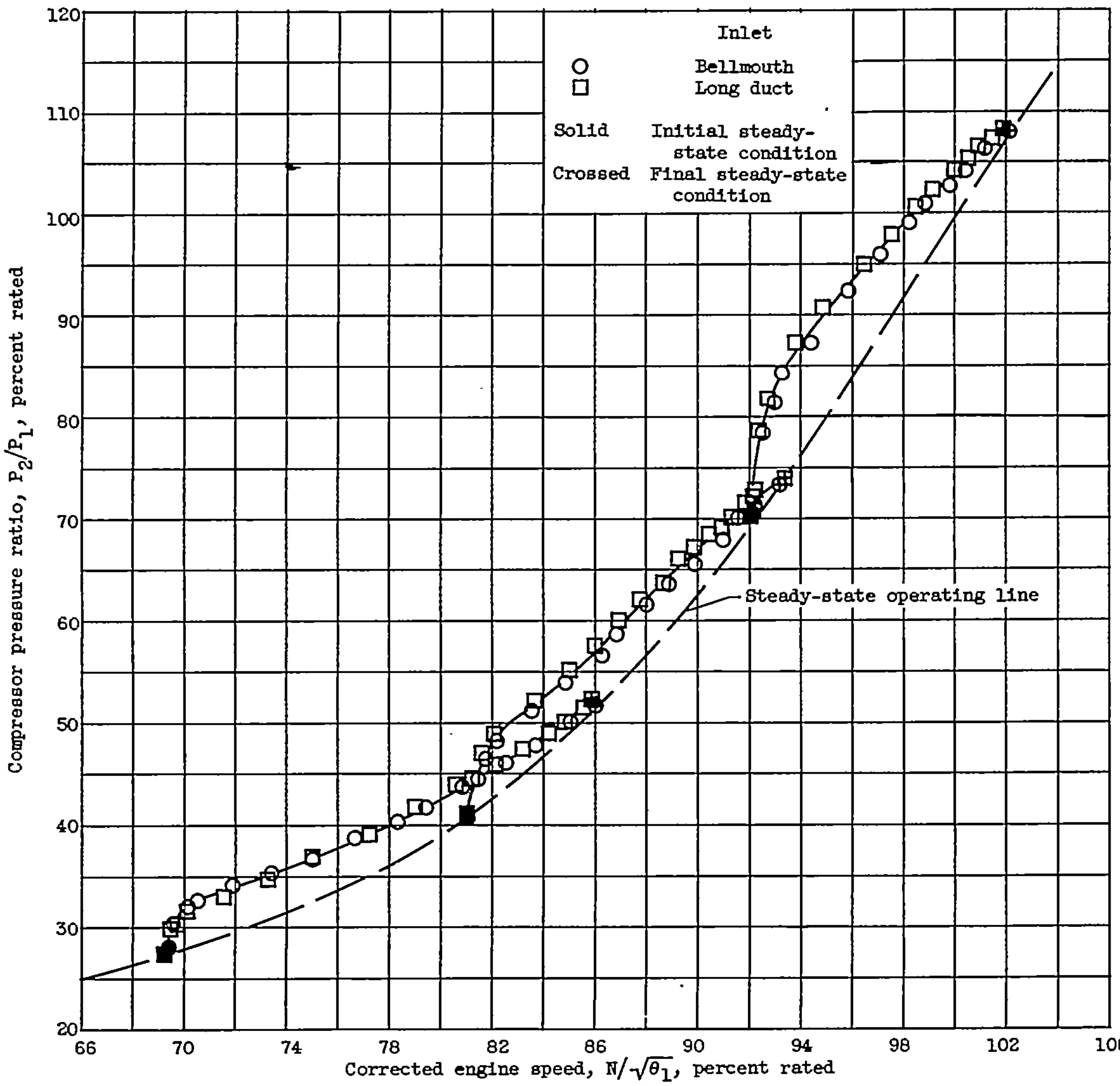
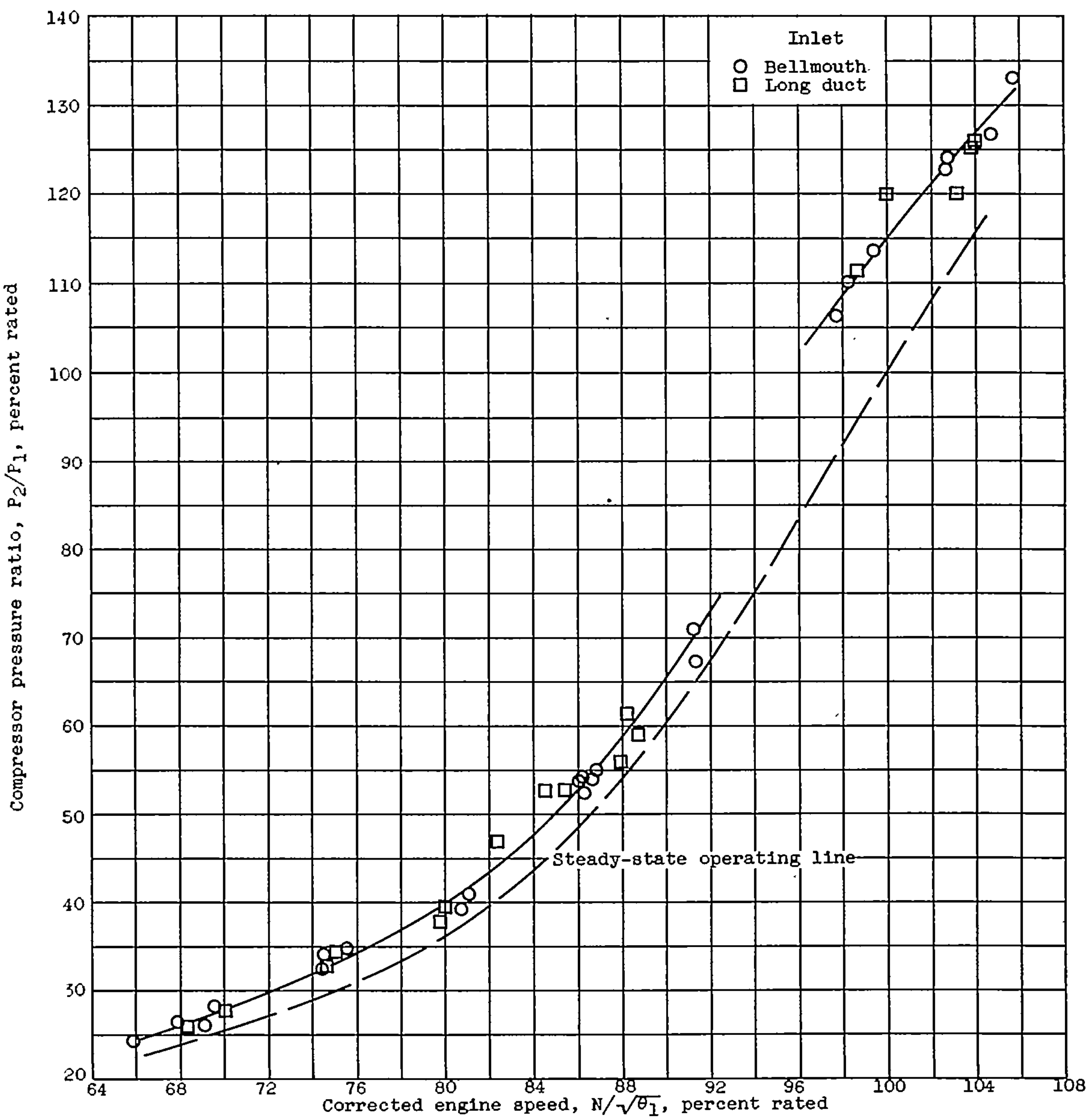


Figure 11. - Typical accelerations with bellmouth and long-duct inlets. Altitude, 35,000 feet; flight Mach number, 0.2; compressor bleeds open.



(a) Compressor bleeds closed. Altitude, 35,000 feet.

Figure 12. - Effect of inlet-duct length on compressor surge line. Flight Mach number, 0.2.

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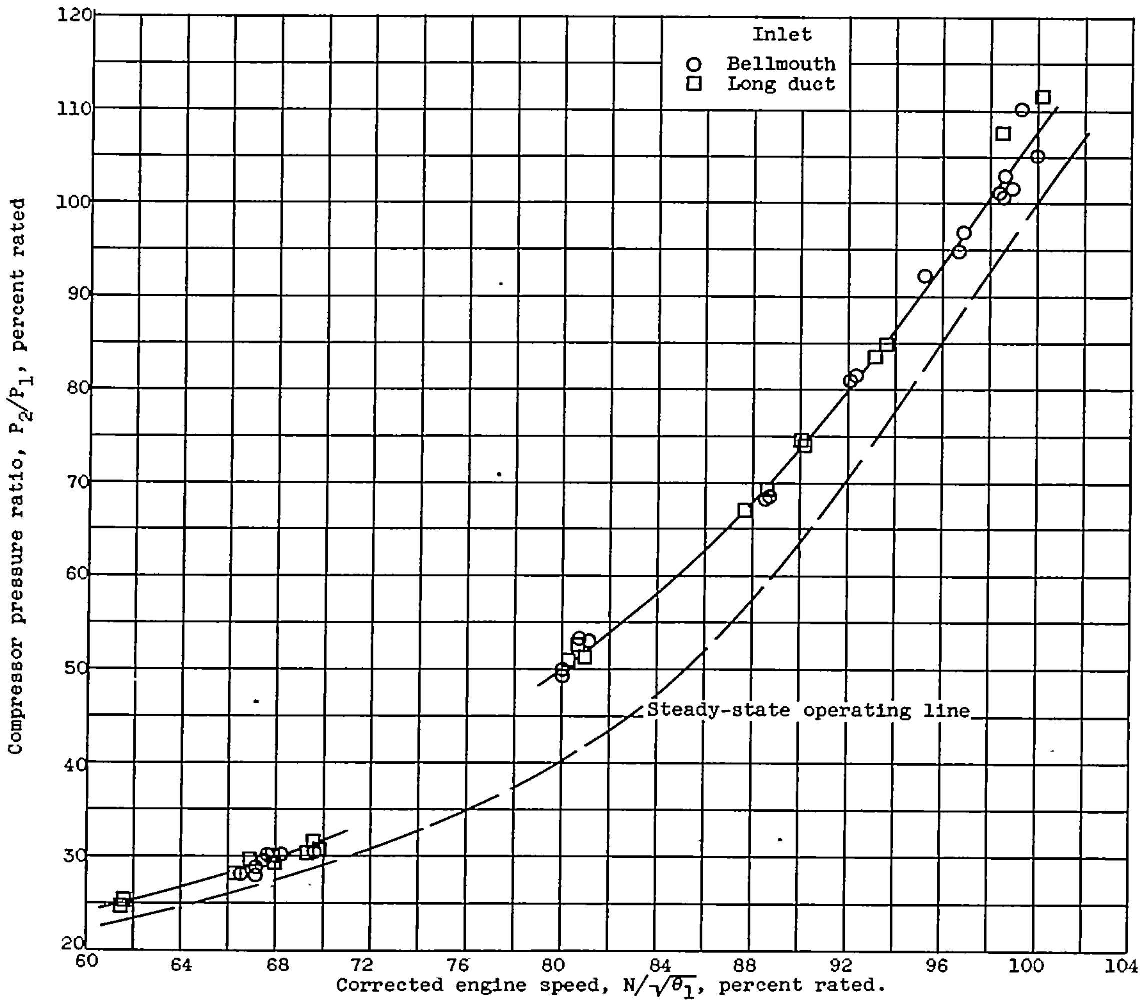

(b) Compressor bleeds open. Altitude, 15,000 feet.

Figure 12. - Concluded. Effect of inlet-duct length on compressor surge line. Flight Mach number, 0.2.

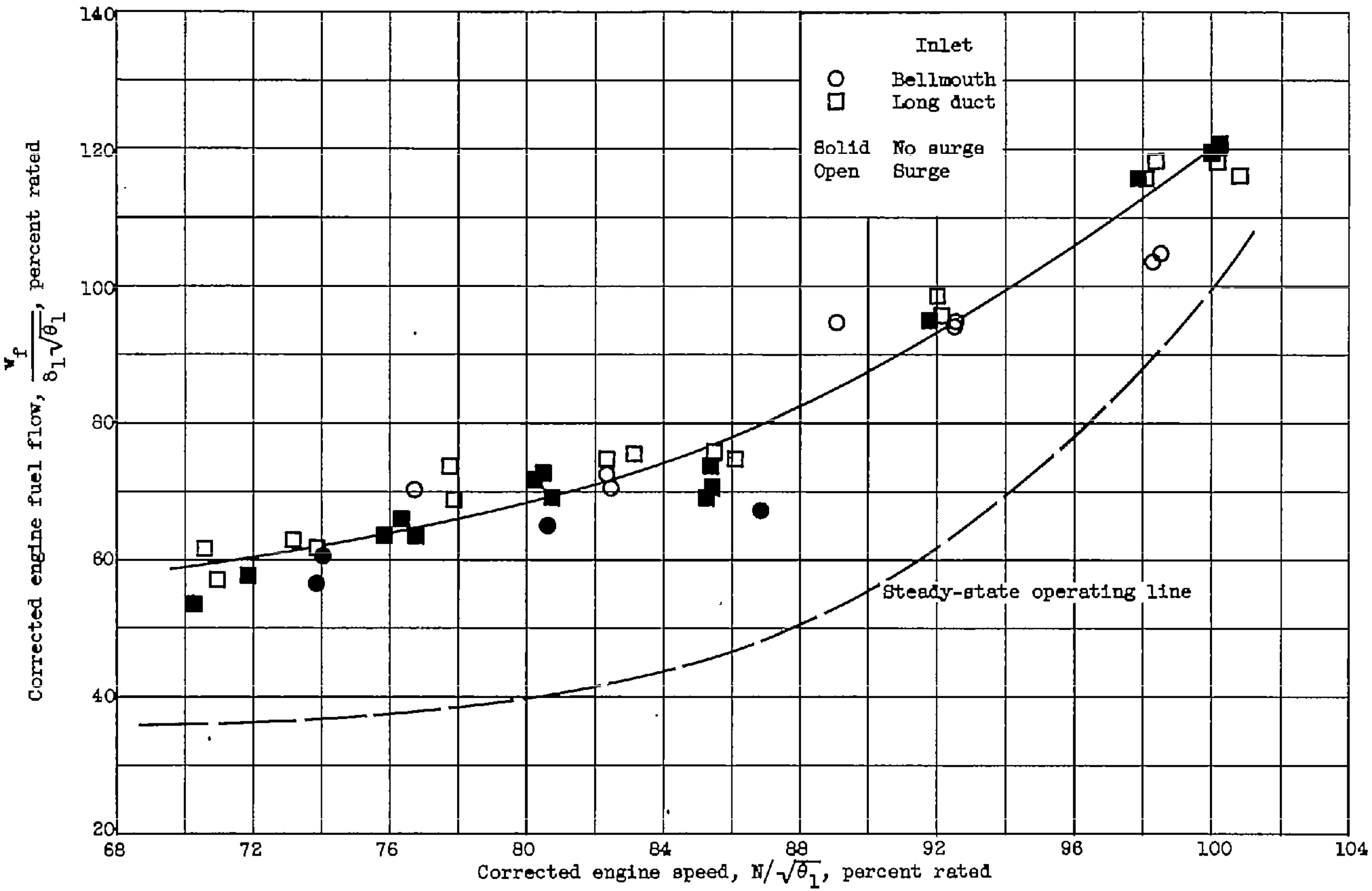

Figure 13. - Comparison of fuel-flow surge limits obtained with bellmouth and long-duct inlets. Altitude, 50,000 feet; flight Mach number, 0.2; compressor bleeds open.

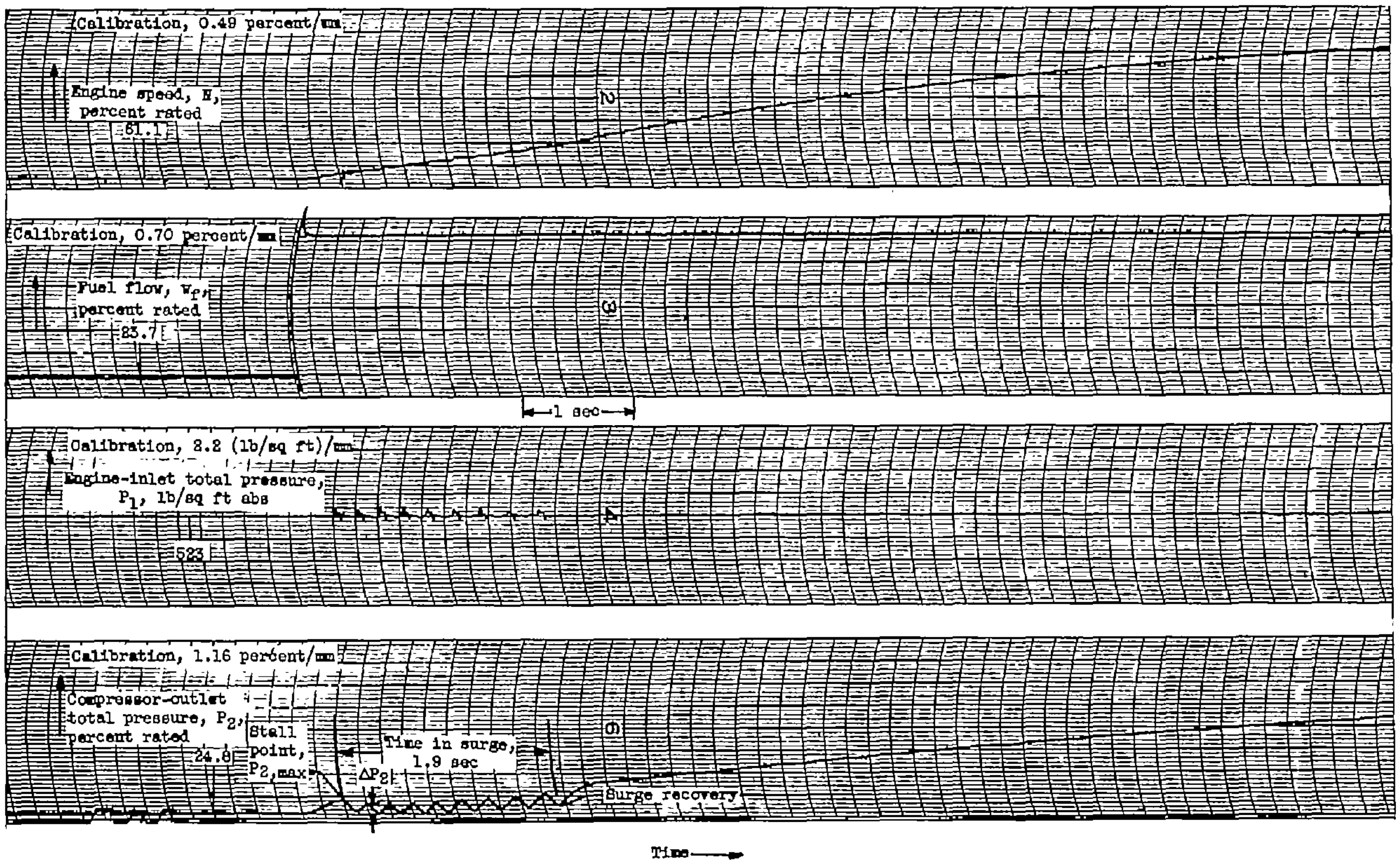

Figure 14. - Typical surge obtained with adequate-sized fuel step. Bellmouth inlet; bleeds closed; altitude, 35,000 feet; flight Mach number, 0.8.

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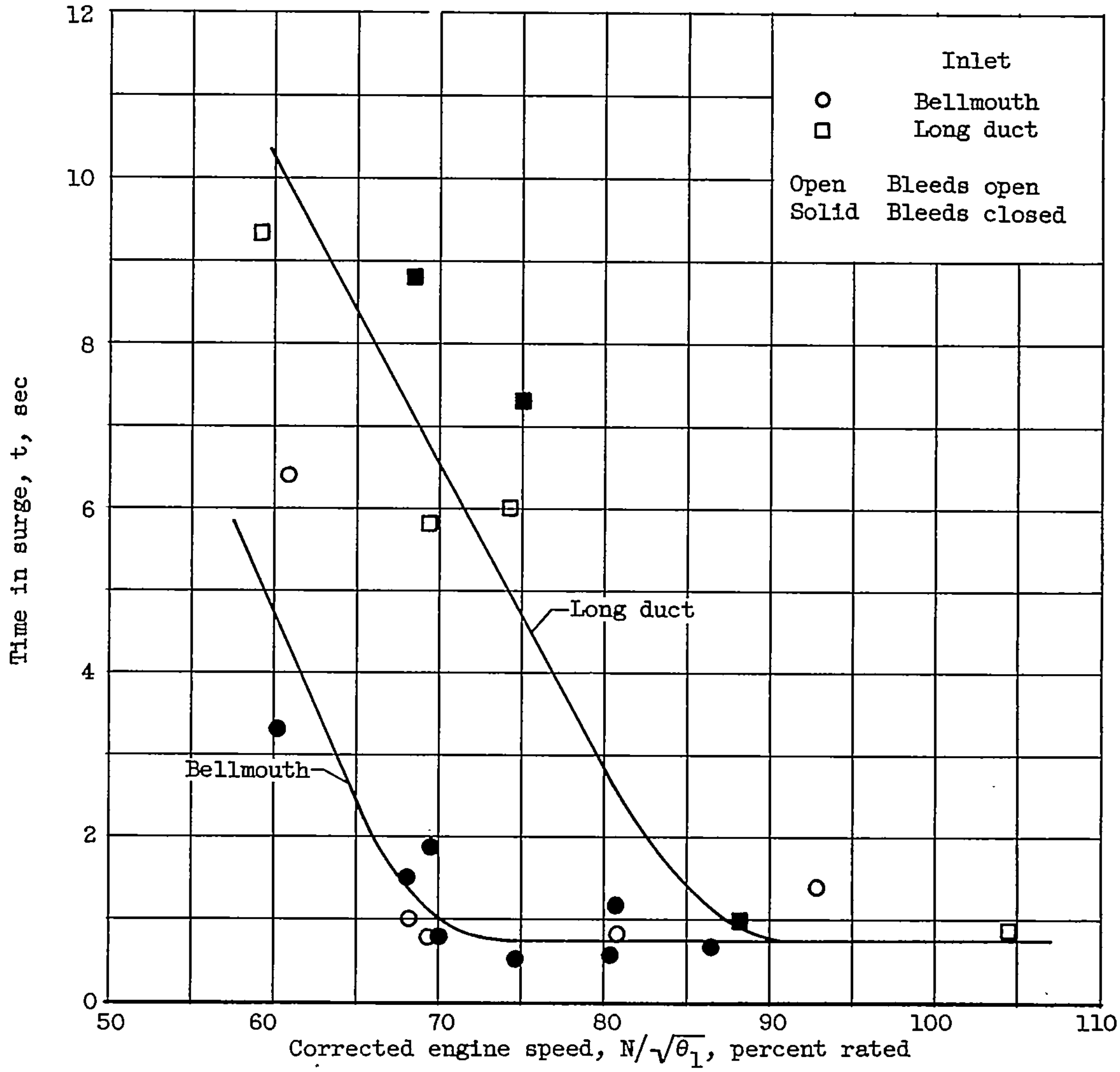

Figure 15. - Effect of inlet-duct length on time engine remained in surge. Altitude, 35,000 feet; flight Mach number, 0.2.

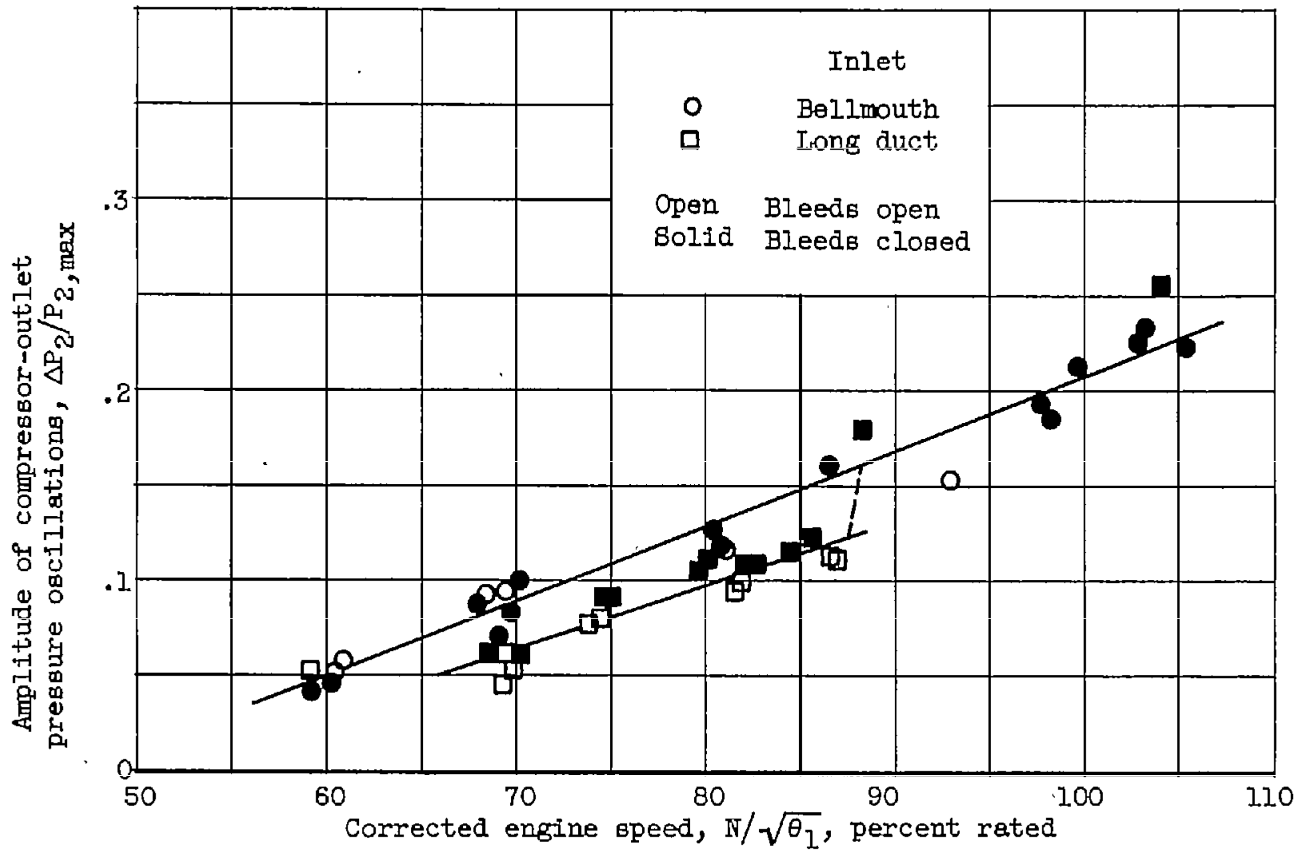

Figure 16. - Effect of inlet-duct length on compressor-outlet pressure oscillations during surge. Altitude, 35,000 feet; flight Mach number, 0.2.

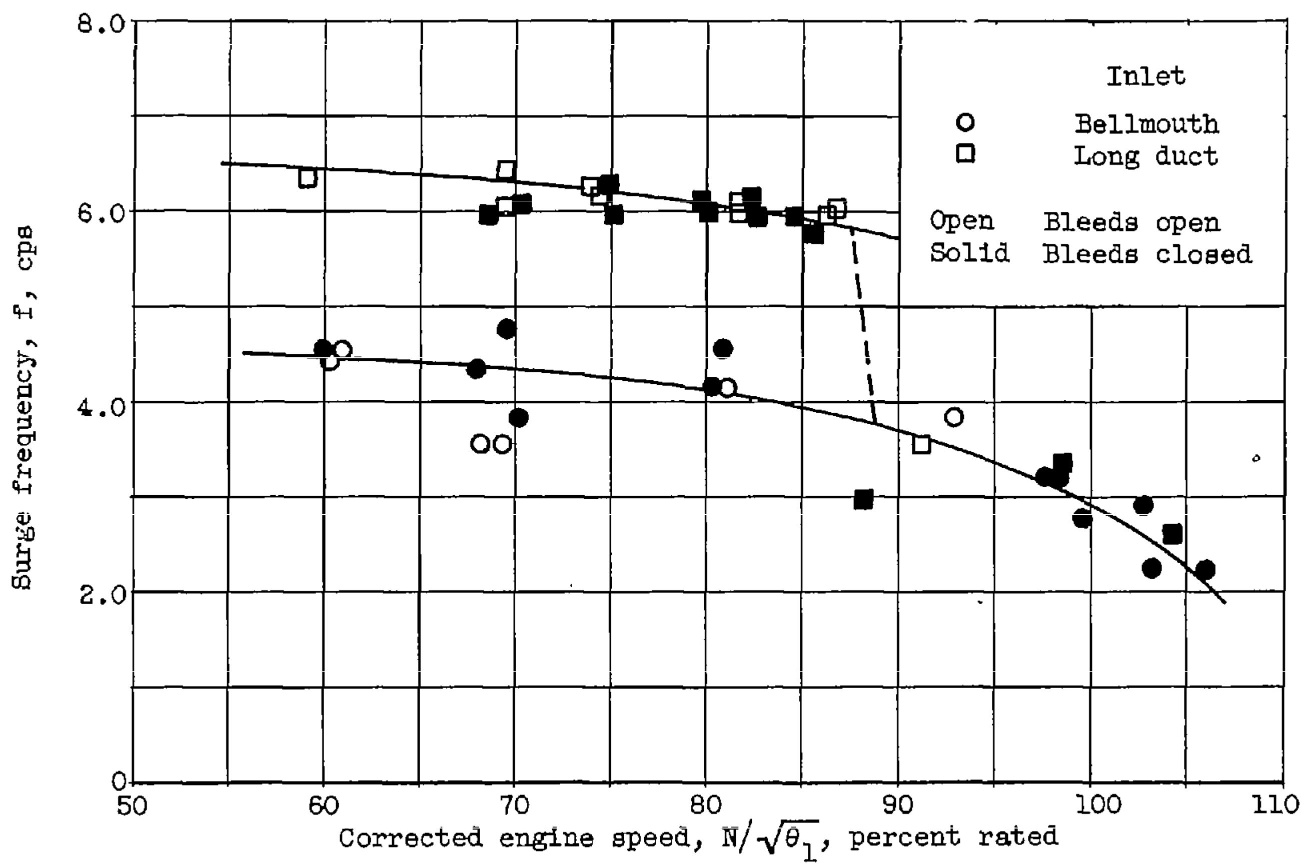

Figure 17. - Effect of inlet-duct length on engine surge frequency. Altitude, 35,000 feet; flight Mach number, 0.2.